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NACA MACH NUMBER WARNING DEVICE

FOR USE IN FLIGHT

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SUMMARY

An instrument for warning the pilot of the approach of the airplane to critical speed conditions has been developed at the Langley Memorial Aeronautical Laboratory. The device closes a contact that completes the electrical circuit of a suitable warning indicator when a predetermined limiting Mach number is approached. The operation of the instrument is based on the relation between Mach number and the ratio of impact pressure to total pressure. These pressures are obtained from the pitot-static installation on the airplane. The accuracy of the device, exclusive of errors due to the pitot-static installation, is ±1 percent.

INTRODUCTION

The maximum safe speed of present-day high-speed airplanes is limited by adverse compressibility effects. The characteristic results of exceeding the safe limit are large changes in trim, stability, and control forces, which are usually dangerous and are sometimes accompanied by severe buffeting. The inordinate changes in pressure distribution around the airplane may cause structural damage to the wings and tail. This condition is usually encountered during dives. These effects occur at a different airspeed for every altitude but, since compressibility effects are a function of only the Mach number, adverse effects always occur at essentially the same value of the Mach number, regardless of altitude, for any one airplane.

The usual method by which the pilot determines the proximity of the airplane to the limiting speed involves reading an altimeter, an airspeed indicator, and a placarded table of predetermined limiting speeds and altitudes for the particular airplane. In high-speed flight or dives, it is obviously difficult for the pilot to correlate these readings quickly. The NACA Mach number warning device was developed to warn the pilot directly when the limiting condition is approached.

PRINCIPLE OF OPERATION

The operation of the NACA Mach number warning device is based on the fact that Mach number is a function of the ratio of impact pressure to total pressure as shown by the relation

$$M^2 = \frac{2}{\gamma - 1}\left[\left(1 - \frac{H - p}{H}\right)^{-\frac{\gamma-1}{\gamma}} - 1\right] \tag{1}$$

where

M Mach number

H free-stream total pressure, pounds per square foot

p free-stream static pressure, pounds per square foot

γ ratio of specific heats (1.4 for air)

The pitot-static tube furnishes the pressures H and p. The warning device utilizes these pressures to close a contact when $(H - p)/H$ reaches a predetermined value. This value is denoted as the operating point of the instrument.

A diagram of the instrument is shown in figure 1. The inner bellows is evacuated and responds to total pressure H. The case is subjected to static pressure p and the outer bellows is therefore actuated by impact pressure $H - p$. The effective areas of the bellows are so proportioned that, at the operating point of the device, the force exerted by the outer bellows is equal and opposite to the force exerted by the inner bellows. Further increase of $H - p$ causes the outer bellows to lift the inner bellows off its stop and thus close the contact.

The bellows-area ratio in terms of $(H - p)/H$ at the operating point of the instrument may be evaluated from the following relations:

$$(H - p)A_1 = (H - 0)A_2$$

$$\frac{A_2}{A_1} = \frac{H - p}{H}$$

[redacted]

and, from equation (1),

$$\frac{H - p}{H} = 1 - \left(0.2M^2 + 1\right)^{-\frac{7}{2}} \tag{2}$$

where

A_1 area of bellows subjected to impact pressure $H - p$, square feet

A_2 area of bellows subjected to total pressure H, square feet

A plot of $(H - p)/H$ against Mach number, sufficiently accurate for field use, is given in figure 2.

GENERAL DESCRIPTION

A basis of design was provided by the NACA Mach number indicator (reference 1). A diagram of a cross section of the warning device is shown in figure 1. Photographs of the device are given as figures 3 to 6.

The inner bellows is evacuated and is prevented from collapsing by an internal stop. The heads of the bellows are fastened together and sealed. An insulated silver contact is attached to the fastening screw. A flat spring fits the collar of the fastening screw and prevents sideshake of the bellows. A fixed contact on a flat spring is mounted directly above the movable contact. Stops prevent overtravel of the bellows when the operating Mach number is exceeded. Adjustments are provided for the internal and external stop screws, inner-bellows height, and contact gap. Both contacts are brought out of the airtight case through insulated and sealed terminals.

The device is constructed entirely of brass and weighs about $2\frac{1}{2}$ pounds.

DESIGN CONSIDERATIONS

The Mach number at which adverse effects are encountered is essentially constant for a particular airplane design, varying only with flight lift coefficient. This limiting Mach number is usually from 0.05 (about 35 mph) to about 0.10 (about 70 mph) greater than the critical Mach number of the airplane, depending upon the particular design. Critical Mach number is defined as the flight

Mach number at which the velocity of air flow at some point on the airplane reaches the speed of sound.

The Mach number at which a warning should be issued can be determined in high-speed wind-tunnel tests or in flight tests. In order to allow for instrument lag, airplane acceleration, and pilot lag, clearance between this limiting Mach number and the Mach number at which the device operates should be provided. The errors introduced by the pitot-static installation of the particular airplane should be taken into account by determining the relation between the actual limiting Mach number and the indicated limiting Mach number for the installation and then basing the operating point of the instrument on the indicated limiting Mach number. A discussion of pitot-static installation errors is given in reference 2.

The actual clearance allowed depends on the maximum acceleration of the airplane near the limiting Mach number and the sum of instrument and pilot lag. The reaction time of the pilot to the warning signal can be easily determined. The instrument lag is difficult to predict, however, since it is possible for the instrument either to lead or lag the operating Mach number; for example, in a dive the static pressure may lag more than the total pressure because of the larger static-side volume and the instrument will therefore issue its signal before the limiting Mach number is actually reached. The clearances needed must therefore be determined by experience. In order to avoid handicapping the performance of the airplane, it is important that the warning device should not issue the signal too soon.

DESIGN FEATURES

The bellows areas in the warning device are large so that large forces are available to actuate and assure positive operation of the contacts. The bellows are quite flexible and the required movement is small with the result that the bellows spring forces are negligible. The instrument is therefore practically independent of the bellows spring forces and the operating point depends on the ratio of bellows areas. Hysteresis, drift, and aftereffects of the bellows are negligible because of the small deflections and low stresses involved. Both bellows are of similar metal and have received the same heat treatments; hence, both should respond similarly to temperature and aging effects and keep the operating point unchanged.

Sliding line contact is present between the large silver contacts to remove oxide film or dirt on the contacts. The current-carrying capacity is sufficiently high that a warning indicator can be actuated without the use of intermediate relays. Welding of the contacts may result in a slightly lower value of operating point on breaking contact than on making contact; however this shift in operating point should be negligible.

LABORATORY TESTS

Laboratory tests of the prototype of the NACA Mach number warning device with an operating point at $M = 0.63$ disclosed the following characteristics:

(1) Altitude effect: ±1-percent shift in operating point between sea level and 30,000 feet. This error might be reduced by a more careful adjustment of the bellows. A residual error of 0.1 percent is inherent in the mechanism because of the bellows spring constants.

(2) Temperature effect: A temperature change of 100° F (from 90° F to -10° F) shifted the operating point less than 1/4 percent. This shift is probably due to stiffening of the bellows.

(3) Contact rating: No adverse effects were noted at voltages of 12 to 24 volts and currents up to 0.5 ampere. For service use, the contacts are conservatively rated at 24 volts and 1/8 ampere, or 110 volts and 0.05 ampere.

(4) Acceleration effects: Accelerations along the bellows axis shifted the operating point 1 percent per g. Accelerations perpendicular to the bellows axis caused a $\frac{1}{4}$-percent shift per 12g. (See installation recommendations.)

(5) Hysteresis: Repeated tests in which the operating point was approached from both above and below indicated that the instrument will always issue its signal within 1/4 percent of the operating point.

(6) Vibration effects: The operation of the instrument was checked while it was being vibrated at 0.04-inch double amplitude and frequencies of 10 to 60 cycles per second. The operating point was found to shift 1/4 percent. After 2 hours of vibration under the same conditions, the operating point was again checked and was found to have shifted 1/4 percent.

(7) Lag: The lag of the instrument is defined as the time elapsing between the attainment of the operating pressure ratio at the pitot-static tube and the issuance of the warning signal. The warning device was connected to 30 feet of tubing 3/16 inch in diameter. A rate of pressure rise equivalent to that occurring when the airplane experiences a longitudinal acceleration of 2g at 500 miles per hour was applied. The lag was less than 0.05 second. Similar tests simulating dives gave the same result.

FLIGHT TESTS

The NACA Mach number warning device used in the laboratory tests (operating point at $M = 0.63$) was installed in the left-wing gun bay of a P-47D airplane (fig. 1). The instrument was bolted firmly to a gun-mount bracket and was connected to a warning light on the instrument panel. Altimeter and airspeed indications were noted by the pilot during shallow dives from 25,000 feet. An indicated airspeed of 300 miles per hour was maintained. Correlation with the altimeter and airspeed indications showed that the warning device made contact at $M = 0.64$ and broke contact at $M = 0.62$.

RANGES AND ADJUSTMENTS

The operating point of the warning device has been shown to depend on the ratio of bellows areas. A sufficiently large selection of bellows sizes is commercially available that a warning device can be designed to give any desired operating point in the existing range of limiting Mach number within ±2 percent. The effective areas are controlled to about 2 percent during manufacture so that bellows can be individually matched to obtain any desired operating point if greater accuracy is warranted.

Further adjustment of the operating point within a 1-percent range can be obtained by permitting a slight amount of residual air in the evacuated bellows. The pressure in this bellows must not exceed 7 millimeters of mercury to avoid temperature and altitude errors. An additional 1-percent shift in the operating point can be obtained by adjusting the contact gap.

In order that the device be free from altitude effect, both bellows must be correctly adjusted. The internal stop must prevent any deflection of the inner bellows when evacuated, and the height of the inner bellows must be adjusted so that the outer bellows is not deflected when the heads are fastened together. Errors in these settings are manifested as a change in operating point with altitude and can be detected by suitable ground tests in an altitude chamber.

RECOMMENDATIONS

The NACA Mach number warning device as developed has been tested and found to be sufficiently accurate for the use described herein. The applications of this device are numerous, as it can be employed to operate any electrical apparatus through the use of suitable relays.

It is recommended that the device be mounted as close as possible to the pitot-static head in order to reduce lag. This location of the instrument is possible in most installations because the device is small and requires only two electrical leads to a warning device on the instrument panel or to the equipment being operated.

The instrument should be installed in a horizontal position with the bellows axis parallel to the lateral axis of the airplane in order to minimize acceleration effects. If vibration is excessive, the use of vibration-absorbing mounts may be advisable.

It is possible, at a sacrifice in accuracy, to decrease the size of the instrument by replacing the bellows with smaller bellows or diaphragms of proper design. The weight can be decreased by using dural in place of brass wherever possible.

The static-pressure and total-pressure volumes may be altered by the use of suitable blocks in order to decrease and equalize lags.

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2. Thompson, F. L., and Zalovcik, John A.: Airspeed Measurements in Flight at High Speeds. NACA ARR, Oct. 1942.

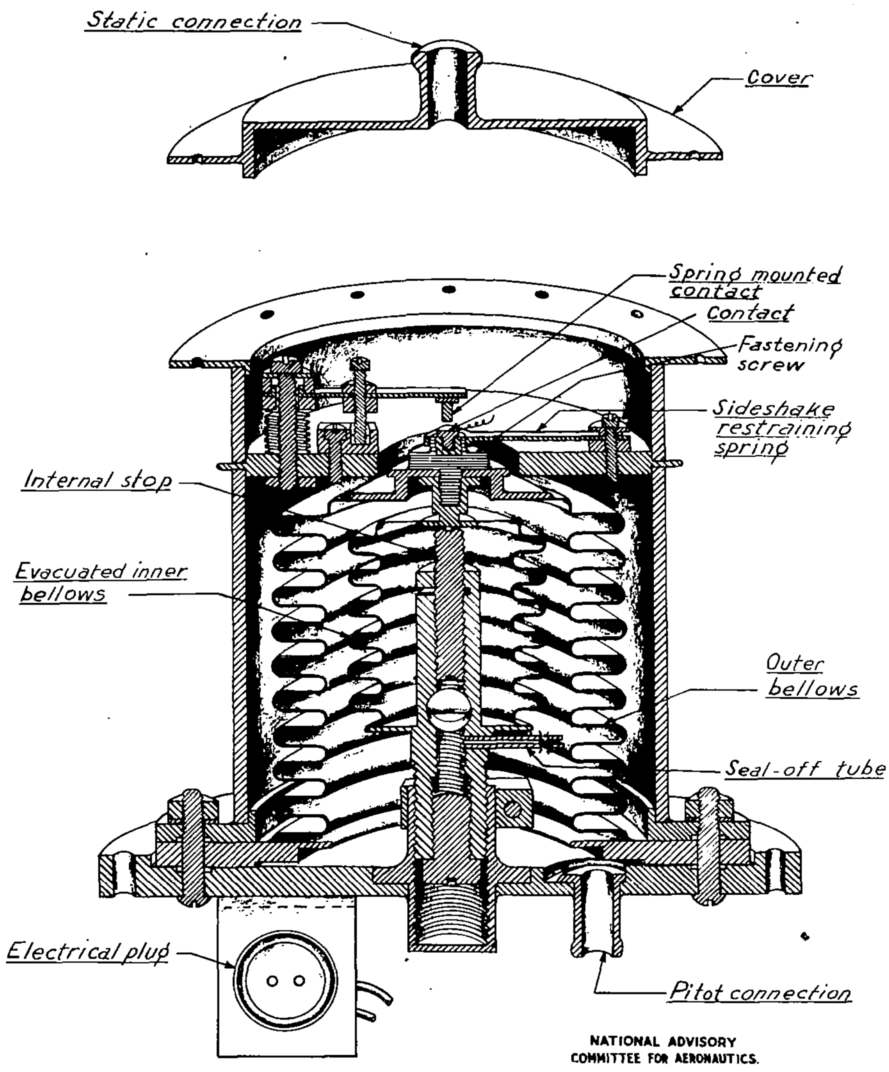

Figure 1.- Cross-sectional view of NACA Mach number warning device.

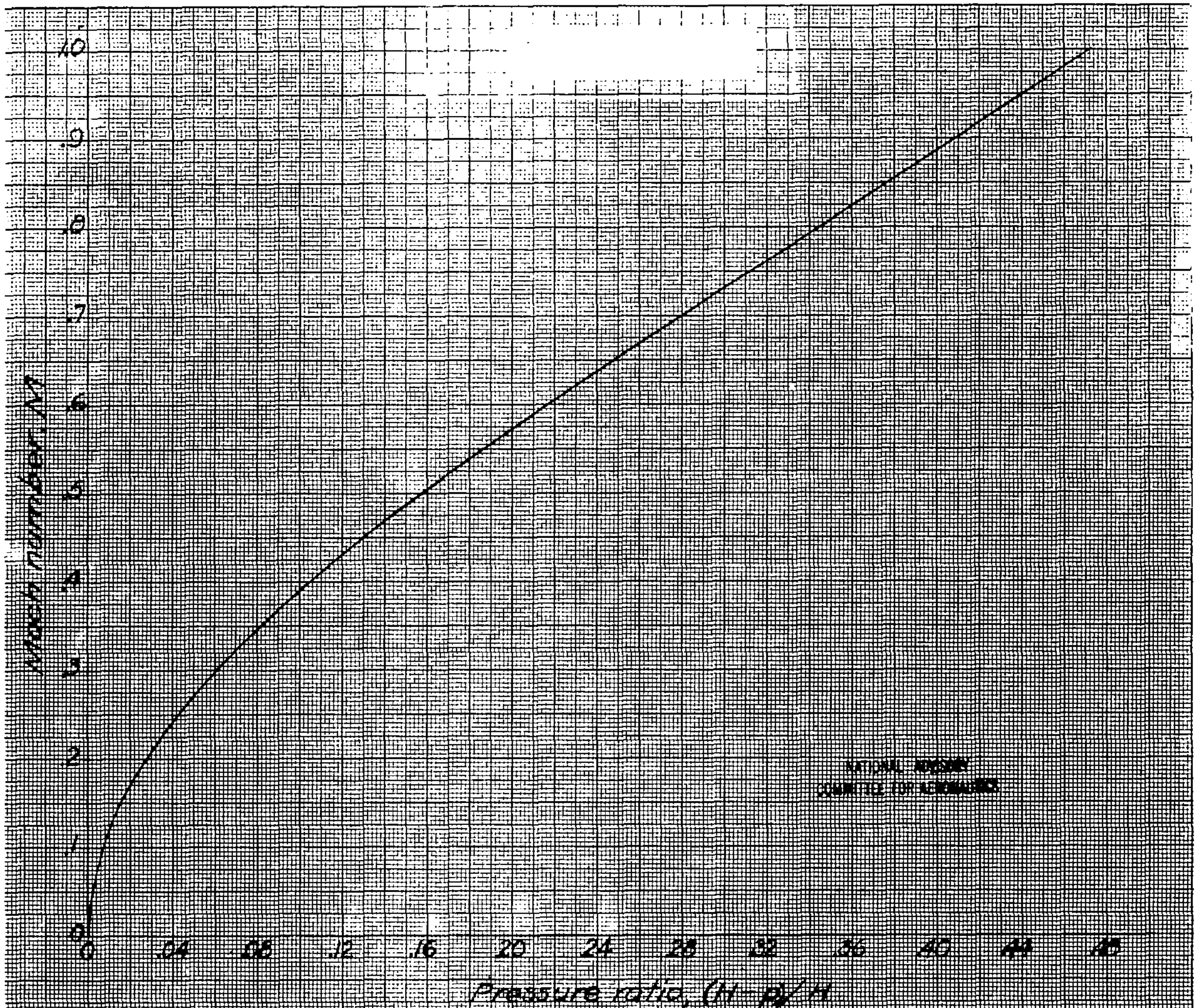

Figure 2.- Variation of pressure ratio (H-p)/H with Mach number.

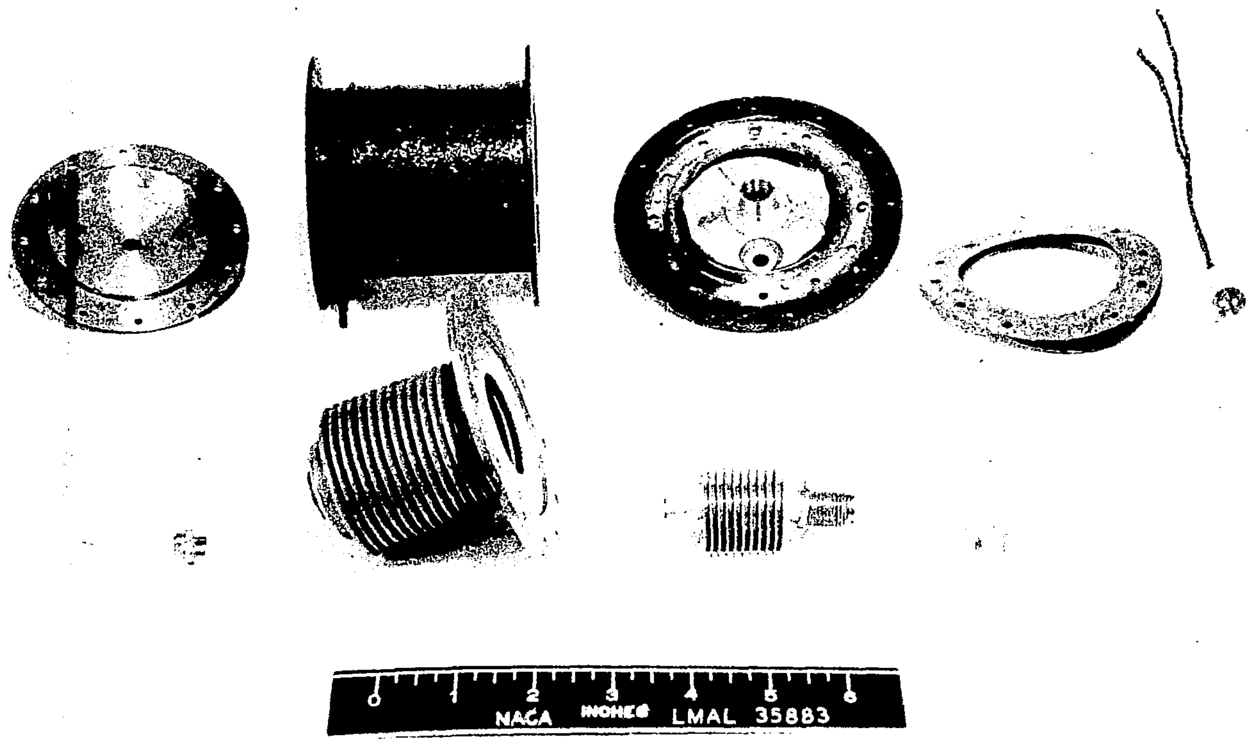

Figure 3.- Disassembled NACA Mach number warning device.

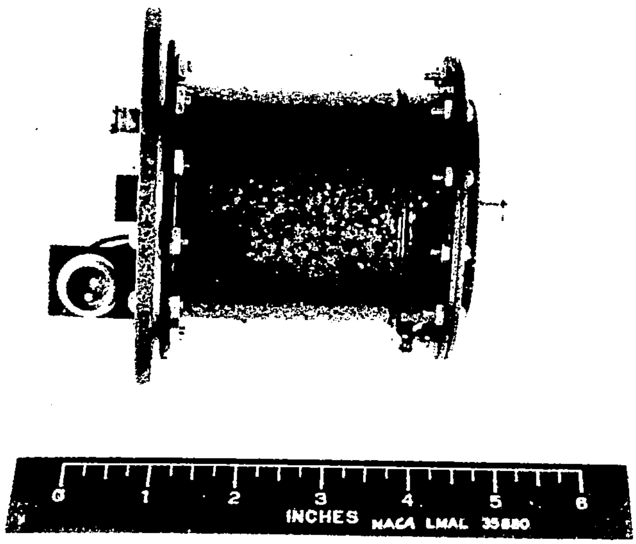

Figure 4.- NACA Mach number warning device.

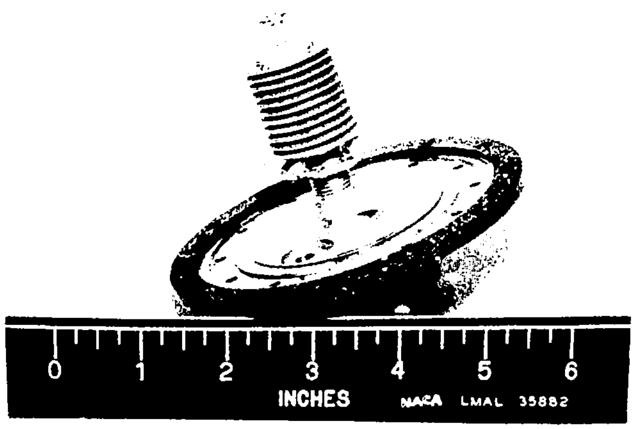

Figure 5.- Evacuated inner bellows of NACA Mach number warning device mounted on base.

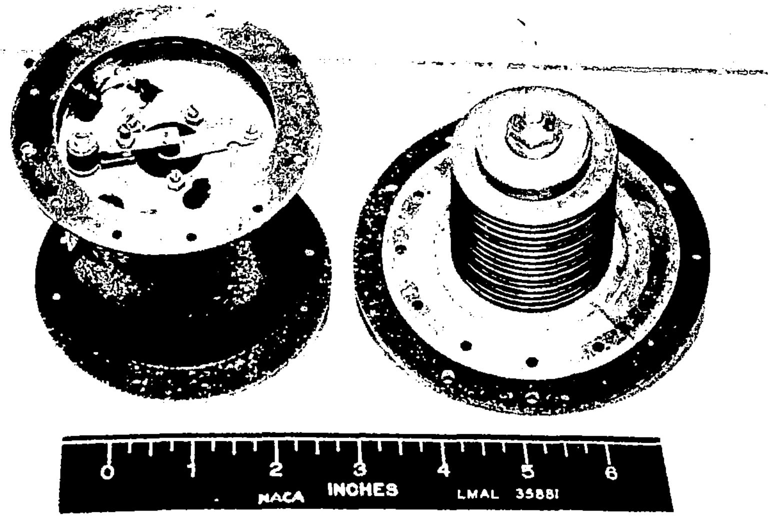

Figure 6.- Contact and terminals of NACA Mach number warning device assembled in case; outer bellows and fastening screw mounted.

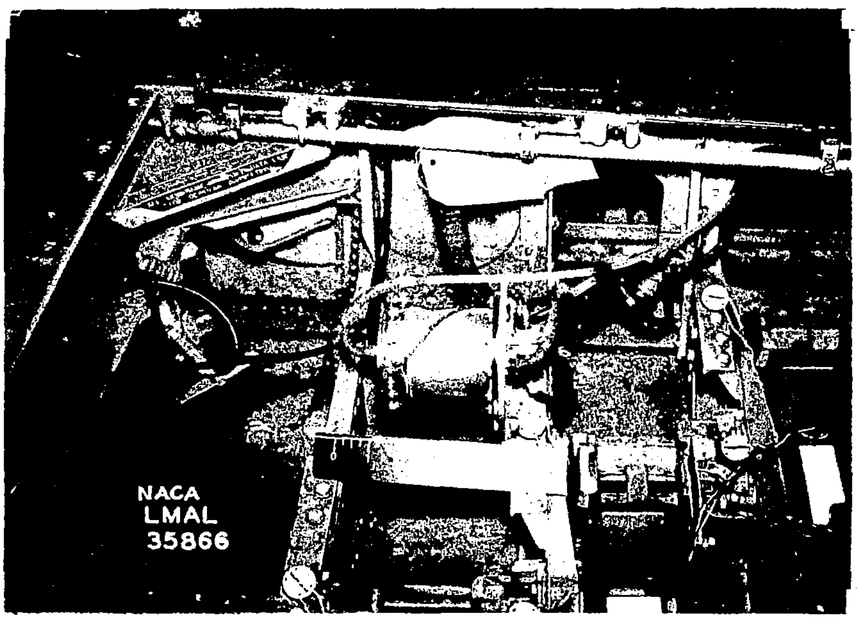

Figure 7.- NACA Mach number warning device installed in left-wing gun bay of P-47D airplane.